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THE SHAPE OF ATOLLS

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SUMMARY

The shape of 99 of the world's 425 atolls has been studied using three types of measurement: form ratios derived from fluvial geomorphology (Miller's Circularity Ratio, R_c; Schumm's Elongation Ratio, R_e; Horton's Form Factor, F), best-fit regular geometric figures (giving an Ellipticity Index, I_e), and actual measurement of shape, by means of best-fit octagons and by the radial line method (giving the I_r index). Atolls cluster rather tightly about a mean shape (mean values: $R_c = 0.57$; $R_e = 0.64$; $F = 0.35$; $I_e = 2.867$; $I_r = 29.78$), and are generally 1.5–3.0 times as long as they are wide. The best-fit octagon method is too coarse to differentiate the relatively homogeneous population of atoll shapes; I_r values are probably not unique; form ratios measure sub-properties of shape which may not reflect shape satisfactorily, and are difficult to interpret, and the Ellipticity Index, I_e, is recommended as a standard of atoll shape. Atolls vary in shape between atoll groups, and the measures suggested here can form a basis for generalised models of atoll origins, marine geology, and ecology.

GENERAL CHARACTERISTICS

The shapes of atolls have been described as oval, annular, or ring-shaped since the time of DARWIN (1842, pp. 19–20), and the similarity of atoll shapes has been used as an argument in favour of particular theories of atoll origin, for example through subsidence of volcanic foundations. Irregularities in form have also been used to develop hypotheses of submarine slumping on submarine volcanic slopes (FAIRBRIDGE, 1950). Many workers have shown, however, that atolls often depart widely from a simple circular or near-circular form. SHEPARD (1963, p.356) writes that Marshall Island atolls "...vary in outline from circular to highly elliptical and even rectangular with bulging corners." WIENS (1962) in his monograph on atoll ecology summarizes shape as follows:

"A study of a number of atoll charts quickly dispels any notion of a uniformity of shapes. ... Atoll shapes cannot be correlated with particular factors that allow for generalisation, except to say that each has its own peculiar shape and, no doubt, reflects the individual submarine contours of its foundation. Every imaginable shape can be found and, with imagination, one can describe their shapes uniquely and individually. It is true, of course, that many, especially among the smaller atolls, are more or less round or oblong. Ebon in the Marshalls is shaped like a circle. Nukuoro in the Carolines is a slightly squeezed circle. Kapingamarangi is more oval. Nomwin is like a pear. Lukunor and Ngaruangle are ham-shaped; and Namomuito, Etal and Namoluk rather triangular. Ujae resembles a stretched out diamond, Taongi a crescent moon, Sorol looks like the outline of a heron, and West Fayu like a headless goose without legs" (WIENS 1962, p.19–25). The literature is scattered with similar attempts to characterise atoll shape by metaphor and analogy (e.g., O. DEGENER and I. DEGENER, 1959).

Such characterisation adds little to knowledge of atoll shape, however, for the shapes of objects such as birds, pork chops or boots are us ally only know as vaguely as those of the atolls themselves. Wiens himself stresses the ecological and theoretical significance of atoll shape, and this, together with the fact that one intuitively assigns atolls to a fairly limited range of shapes, makes the quantification of atoll shape advisable. Recent work on the effect of Pleistocene sea-level shifts on atoll shapes (MACNEIL, 1954) and on atolls as ecosystems (FOSBERG, 1961) suggests the need for a standard of atoll shape, and for the quantitative investigation of the range of shape variation. Few attempts have so far been made to generalise about atoll characteristics from large samples. If atoll shapes are indeed as variable as Wiens suggests, then the search for shape standards will probably be fruitless. If, however, atoll shapes cluster rather tightly about a mean value, then generalisation within and between atoll groups will be possible. The definition of a measure of atoll shape, furthermore, invites the analysis of such shape controls as structure and ecologic factors on a statistical basis, with the ultimate aim of generalising about gross atoll morphology.

Shape is an elusive and complex property of objects: in another, but relevant context, the *Shorter Oxford English Dictionary* defines it as "a figure dimly or uncertainly perceived". The properties of shapes are many and may easily be measured: they include length, breadth, perimeter, area, relief, slope and orientation. Each is individually inadequate as a measure of shape, but taken in combination they may give some indication of variation in a collection of shapes. Operations on these primary measurements have been used in the study of river basin shapes; the method is referred to here as that of *form ratios*. Alternatively, a shape may be compared to that of a better known object. GASTALDI's (1873) comparison of mountain cirques and armchairs, for example, and Wiens's descriptions of atoll shapes fall into this category. On a more precise level the comparison may be made with regular geometric figures: circles, rectangles and more complex figures. Several writers have applied such terms as circular or oblong in a rather loose manner when describing atolls. In geomorphology such similarities have been quantified, as in the use of lemniscates to describe the shapes of drainage basins and drumlins (CHORLEY et al., 1957; CHORLEY, 1959). This method may be termed that of *best-fit regular geometric figures*.

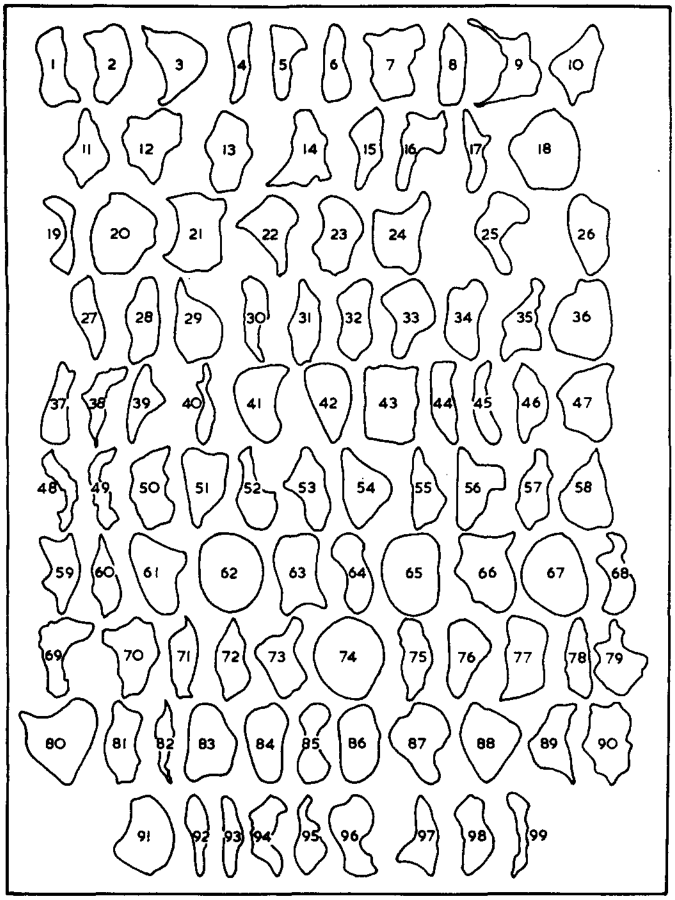

Fig.1. Sample atolls, not drawn to scale and with arbitrary orientation. The atolls shown are listed below.

1 = Abaiang
2 = Abemama
3 = Addu
4 = Ailinginae
5 = Ailuk
6 = Aldabra
7 = Ant
8 = Ari
9 = Arno
10 = Atafu
11 = Aur
12 = Beautemps-Beaupré
13 = Bikini
14 = Butaritari
15 = Canton
16 = Christmas
17 = Eauripiik
18 = Ebon
19 = Elato
20 = Eniwetok
21 = Fadiffolu
22 = Fakaofo
23 = Fanning
24 = Faraulep
25 = Felidu
26 = Gaha Faro
27 = Gardner
28 = Glover's
29 = Hadummati
30 = Hao
31 = Helen
32 = Hull
33 = Ifalik
34 = Ihavandiffulu
35 = Jaluit
36 = Kolumadulu
37 = Kuop
38 = Kwajalein
39 = Lamotrek
40 = Lighthouse
41 = Losap
42 = Lukunor
43 = Maiana
44 = Majuro
45 = Makunudu
46 = Maloelap
47 = Manihiki
48 = Mellish
49 = Miladummadulu
50 = Mili
51 = Mulaku
52 = Murilo
53 = Mururoa
54 = Namoluk
55 = Ngatik
56 = Ngulu
57 = Nggelelevu
58 = Nomwin
59 = Nonouti
60 = North Mahlos
61 = North Male
62 = North Minerva
63 = Nukufetau
64 = Nukulaelae
65 = Nukumanu
66 = Nukunono
67 = Nukuoro
68 = Onotoa
69 = Ontong Java
70 = Oroluk
71 = Osprey
72 = Pakin Pagenema
73 = Pingelap
74 = Pratas
75 = Pulap
76 = Puluwat
77 = Rakahanga
78 = Raroia
79 = Rongelap
80 = Rongerik
81 = Satawan
82 = Sorol
83 = South Mahlos
84 = South Male
85 = South Minerva
86 = South Nilandu
87 = Tuvadiva
88 = Sydney
89 = Sarawa
90 = Tongareva
91 = Tova
92 = Turneffe
93 = Ujelang
94 = Ulithi
95 = West Fayu
96 = Woleai
97 = Wotho
98 = Wotje
99 = Zohhouyoru

Finally, it should be possible to derive some measure of shape which is independent of magnitude and orientation, and which measures shape alone. Among geographers, BUNGE (1962) and BOYCE and CLARK (1964) have begun to work on such methods of *direct shape measurement*.

Each of these methods has been applied to a total of 99 atolls selected from published Admiralty charts, supplemented by Newell's chart of Raroia Atoll (NEWELL, 1956) and Stoddart's charts of Turneffe, Lighthouse and Glover's Reefs (STODDART, 1962). The atolls chosen represent about 23% of the total known number of atolls (BRYAN, 1953); the sample atolls are listed and are shown irrespective of size and orientation in Fig.1. Table I shows the distribution of sample atolls by atoll groups. Analyses were carried out by student operators in morphometry classes at Cambridge University in 1964 and 1965.

TABLE I

DISTRIBUTION OF SAMPLE ATOLLS BY ISLAND GROUPS

Group	*Total number of atolls*[1]	*Sample studied*[2]
Caroline	41	27
Maldive	24	17
Marshall	33	16
Gilbert	16	7
Ellice	9	2
Tokelau	4	3
Cook	9	3
Phoenix	7	3
Tuamotu	75	3
Solomon	6	2
Caribbean	27	3
Other	174	13
Totals	425	99

[1] Data on total numbers of atolls in each group from the list by BRYAN (1953).
[2] For the names of individual atolls and for maps of their shape, irrespective of size, see Fig.1.

METHODS

Form ratios

The form ratios used were drawn from fluvial geomorphology, and were primarily developed to measure drainage basin shape.

Horton's Form Factor (HORTON, 1932), F, is given by:

$$F = \frac{A_1}{L_1^2}$$

where A_1 is atoll area in square nautical miles, and L_1 is the length of the longest axis of the atoll in nautical miles.

Miller's Circularity Ratio (MILLER, 1953, p.8), R_c, is given by:

$$R_c = \frac{A_1}{A_2}$$

where A_1 is atoll area in square nautical miles, and A_2 is the area of a circle with the same perimeter as that of the atoll.

Schumm's Elongation Ratio (SCHUMM, 1956, p.612), R_e, is given by:

$$R_e = \frac{d}{L_1}$$

where d is the diameter of a circle with the same area as the atoll, and L_1 is the length of the longest axis of the atoll in nautical miles.

Best-fit regular geometric figure

Inspection shows that atolls approach a circular or elliptical form, and theory suggests that atolls should develop such a form during subsidence. Since a circle is a special case of the ellipse, the latter was chosen as the basis of a shape index, as follows. The area of an ellipse is given by $A_e = \pi ab$, where a is half the long axis and b half the short axis. Let A_e equal the area of the atoll, and let a equal half the length of the long axis of the atoll, L_1; solve for b. This gives both long ($2a = L_1$) and short ($2b$) axes of the ellipse whose area corresponds to that of the atoll, when the long axes of the two are the same. The *Ellipticity Index*, I_e, is given by:

$$I_e = \frac{2a}{2b} \text{ or } \frac{L_1}{2b}$$

when b is given by:

$$b = \frac{A_1}{\pi \left[\frac{L_1}{2} \right]}$$

Direct shape measurement

Two methods are used to measure shape itself, rather than its attributes, irrespective of size and orientation. The first is developed by BUNGE (1962), based on the fact that shapes can be approximated by equal-sided polygons whose vertices lie on the perimeter of the shape. Metal eight-sided polygons with hinged vertices were used, with each side 6 inches long; each atoll was mechanically enlarged or reduced until it matched the polygon, with the eight vertices on or close to the atoll margin (Fig.2). The polygon thus formed can be described by summing the distances between all

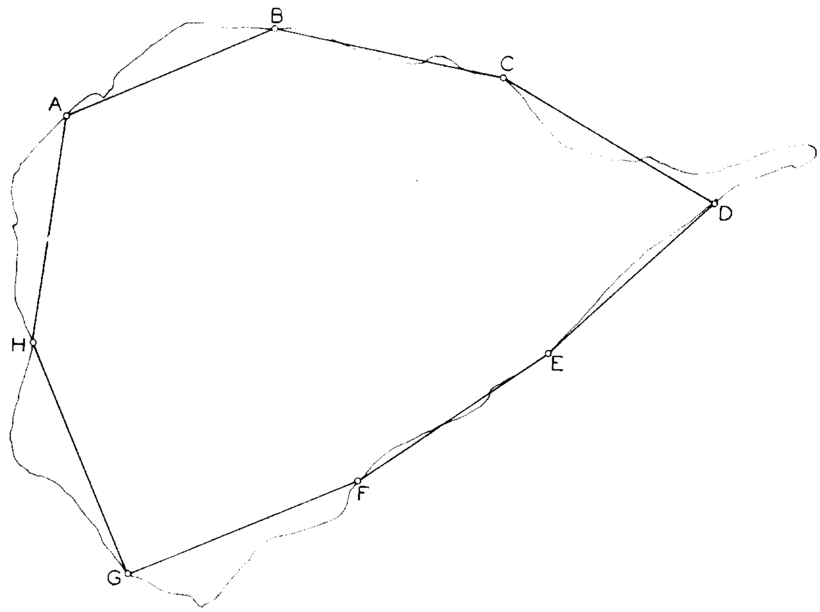

Fig.2. Best fit of an eight-sided polygon to Nomwin Atoll.

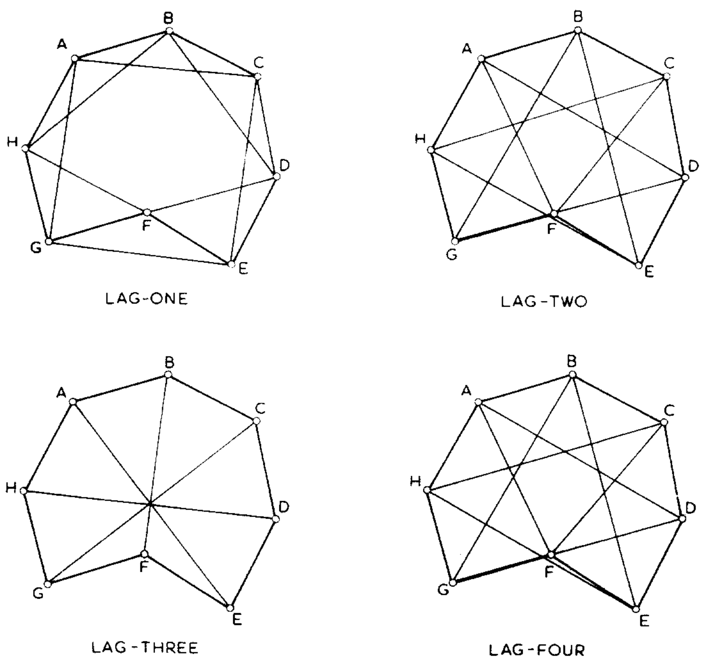

Fig.3. Measurements of lag distances for an eight-sided polygon.

the vertices lag-one, lag-two,... until all unique sums are determined; and by squaring and then summing the distances between all vertices lag-one, lag-two, ..., until all unique squared sums are determined. Each shape will then have a one-to-one correspondence with one of these sets of sums (BUNGE 1962, pp.72–80).

In Fig.3 the eight-sided polygon is fitted to the shape shown, and its vertices are given by A, B, ... H. Distances lag-one (S_1) are given by AC, BD, CE, ... HB, i.e., one vertex is skipped. Distances lag-two (S_2) are given by AD, BE, CF, ... HC; i.e., two vertices are skipped. Distances lag-three (S_3) are given by AE, BF, CG, ... HD; i.e., three vertices are skipped. Distances lag-four, given by AF, BG, ... HE, are identical in an eight-sided polygon with distances lag-two, and distances lag-five with those lag-one: these sums are not unique and hence are not calculated. For an eight-sided polygon six values are derived (S_1, S_2, S_3, S_1^2, S_2^2, S_3^2) which uniquely describe its shape.

The last method, described by BOYCE and CLARK (1964) is termed the radial line method. The atollshape is mechanically reduced to a convenient size, outlined on heavy card and cut out. The centre of gravity of the shape thus formed is determined. With this as centre, overlay a polar grid with radial lines at intervals of 22.5°, giving 16 radial lines (Fig.4). Calculate the values of the length of each radial line (r) as a percentage of the total lengths from the centre of gravity to the boundary of the shape. If the shape is a circle each radial line will have a value of 6.25% of the total; call this value R. Sum the differences between R and each percentage value of r, ignoring the sign, to give a radial line shape index, I_r.

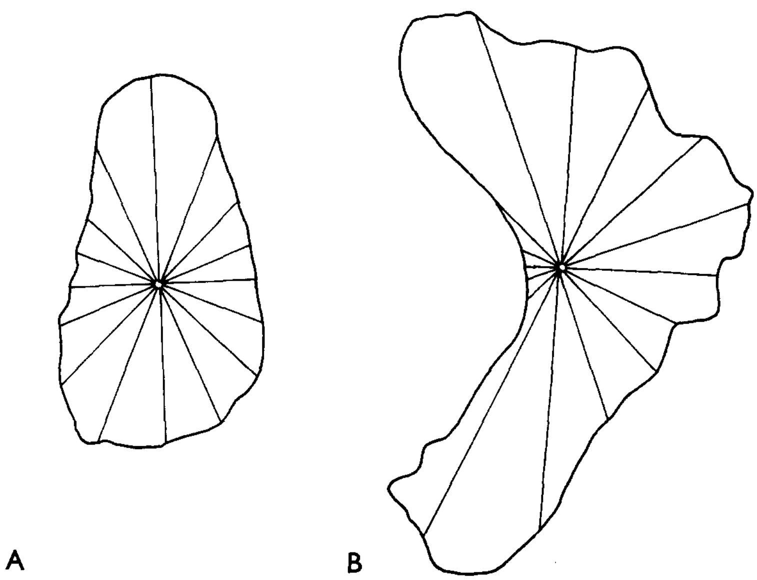

Fig.4. The radial line method applied to (A) South Male Atoll and (B) Ontong Java Atoll.

The derivation may be stated as follows:

$$I_r = \sum_1^n \left| \left[100 \cdot \frac{r_1}{\Sigma_1^n} - \frac{100}{n} \right] \right|$$

Boyce and Clark apply the method to the shape of central business districts in towns, and find that a circle has I_r value of 0, a square of 12, a cross of 18, a star of 25, a rectangle of 28, and a straight line of 175.

RESULTS

The 99 atolls studied varied in length (L_1) from 2.10–80.4 nautical miles, in breadth (L_2) from 1.3–36 nautical miles, and in area from 1.78–1,078 square nautical miles. Mean and median values for all the sampled atolls are given in Table II.

TABLE II

MEAN AND MEDIAN VALUES FOR 99 ATOLLS

Length L_1		*Breadth L_2*		*Perimeter P_1*		*Area A_1*	
mean	*median*	*mean*	*median*	*mean*	*median*	*mean*	*median*
16.3	13.0	8.6	6.45	44.40	36	127.7	52.93

The relationships between length and breadth and between perimeter and area are linear, though in the former case with considerable scatter, when plotted on logarithmic paper (Fig.5). This suggests that the shape population is a relatively homogeneous one.

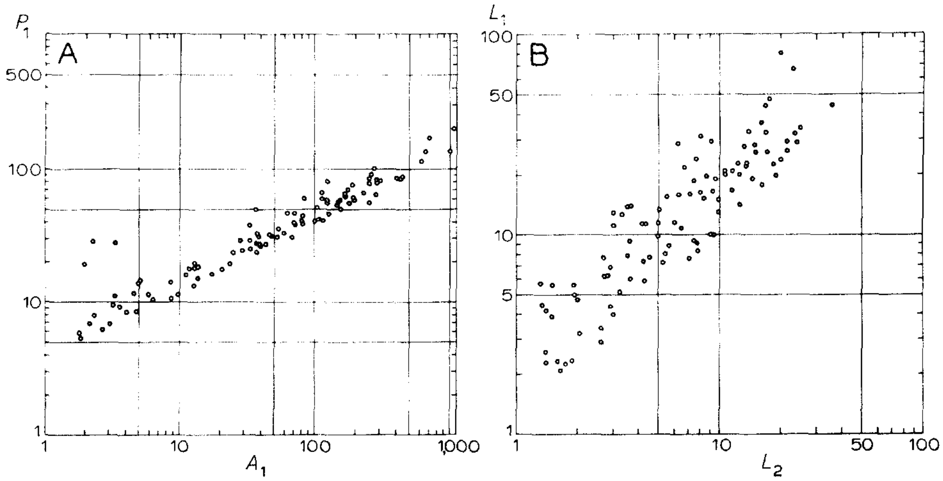

Fig.5. Relationships between (A) perimeter and area, and (B) maximum length and breadth, for the 99 sample atolls. Linear measurements in nautical miles; areal measurements in square nautical miles.

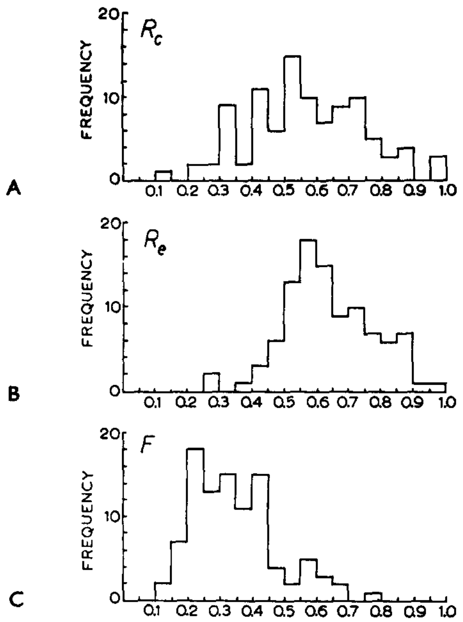

Fig.6. Histograms showing the (A) distribution of R_c, (B) R_e, and (C) F values for the sample atolls. A. N = 99; $\overline{R_c}$ = 0.5689; $R_{c\,MD}$ = 0.554; σ = 0.1857. B. N = 99; $\overline{R_e}$ = 0.6379; $R_{e\,MD}$ = 0.623; σ = 0.1425. C. N = 96; $\overline{F}$ = 0.349; F_{MD} = 0.334; σ = 0.1334

Form ratios

Values for R_c, R_e and F were ranked and plotted as histograms in Fig.6. Mean values for each were, respectively, 0.57, 0.64 and 0.35. The median nine atolls selected by each method were noted, and of the 27 atolls so selected only one appeared in more than one list, suggesting that the three form ratios are measuring fundamentally different attributes of shape. They may also involve the use of primary measurements which are independant of shape. Thus Miller's R_c uses the area of a circle with the same perimeter as that of the atoll, but an atoll with a highly crenulate perimeter may have a similar gross shape to one with a shorter outline. Similarly, the primary measurements for Horton's F, the ratio of length and area, may indicate shape in only a very coarse manner. Form ratios are, therefore, probably not wholly satisfactory measures of shape, and it is in addition difficult to visualise their meaning. The histograms of the distributions of each of the form ratios, however, with their fairly low standard deviation about the mean, indicate that the shapes concerned are probably fairly tightly clustered.

Ellipticity index

The ellipticity index, I_e, varies from 1.023, the most circular atoll (North Minerva) o 7.91, the most elliptical (Ari Atoll). The frequency distribution is highly skewed, but may be normalised by plotting the logarithms of I_e values (Fig.7). The mean I_e value is 2.867, but because of the skewness of the distribution, the modal class, between 1.5 and 2.0, is a better measure of central tendency. The atolls with the nine median I_e values were again selected, and seven of these were in the median nine selected by Horton's F number. Only one atoll in each case was common to the median nine selected by I_e index and by R_e and R_c numbers. The correspondence between I_e index and F number is to be expected, since both result from operations on atoll long axis and atoll area. The ellipticity index shows that, with a given area and length, atolls tend to be about 1.5–3 times as long as they are wide.

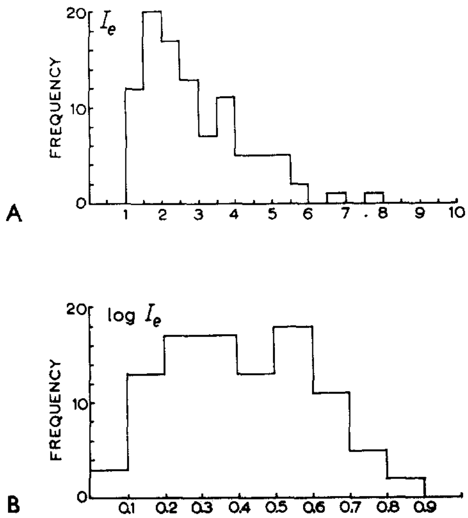

Fig.7. Histograms showing the distribution of I_e and log I_e values for the sample atolls. A. N = 99; $\overline{I_e}$ = 2.867; $I_{e\ MD}$ = 2.352. B. N = 99; $\overline{\log I_e}$ = 0.4085; σ = 0.1911.

Polygon measures

The values of S_1, S_2, S_3, S_1^2, S_2^2, and S_3^2, derived from the lag measures of the fitted octagons, were computed for the sample atolls, and the values plotted as frequency curves in Fig.8. All values except S_2^2 are normally distributed with low dispersion, giving single peaked curves. The conclusion is drawn that the shapes measured are so similar that the polygon method is too coarse to differentiate them. The distributions may be compared with those of BUNGE (1962, pp.80–87) for Mexican rural communities, where highly diverse shapes give multimodal histograms, and could be classed by taking the low frequency points as class intervals. In the case of atolls, the distributions indicate no more than similarity of atoll shapes.

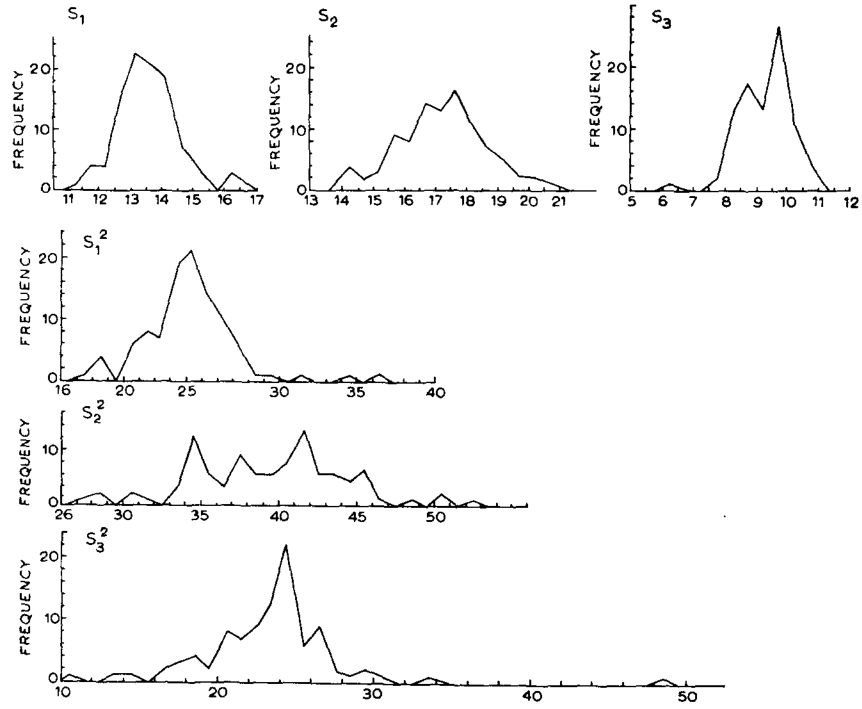

Fig.8. Distributions of S values derived from polygon-lag measurements for the sample atolls.

Radial line index

Values of I_r are plotted as a histogram in Fig.9. The values range from 5.23, the most circular (Pratas Atoll: compare 6.47 for North Minerva), to 79.4, the most elongate (Zohhouyoru). The mean value is 29.78 and the median 28.33 (Satawan Atoll): Satawan is also among the median nine atolls selected by the I_e and F methods. Within one standard deviation from the mean, values of I_e range from 15.05–44.51.

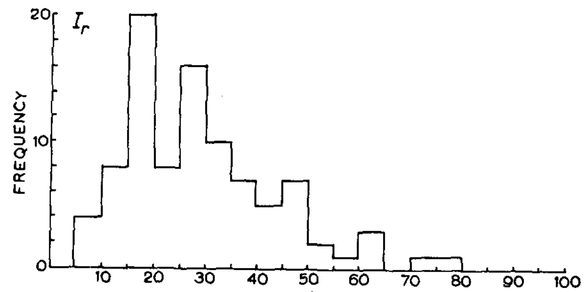

Fig.9. Histogram showing the distributions of I_r values for the sample atolls. N = 93; $\overline{I_r}$ = 29.78; $I_{r\,MD}$ = 28.33; σ = 14.73.

According to Boyce and Clark these values lie in the range of squares, crosses, stars and rectangles.

COMMENT ON METHODS

Ideally, measures of shape should be (*1*) meaningful measures of shape itself, rather than of its sub-properties; (*2*) simple to calculate; (*3*) expressible in terms of a single index, which (*4*) can be readily restated in shape terms. None of the methods used are fully satisfactory by these standards. The form ratios are crude but easily measured indices which do not actually measure shape itself. Of the three methods used, Horton's F is preferred, since it is the easiest to calculate, and the results are most closely matched by other methods. The form ratios are particularly useful where the shapes themselves are relatively homogeneous; difficulties could arise where, for example, the degree of perimeter crenulation varied widely from atoll to atoll. Bunge's

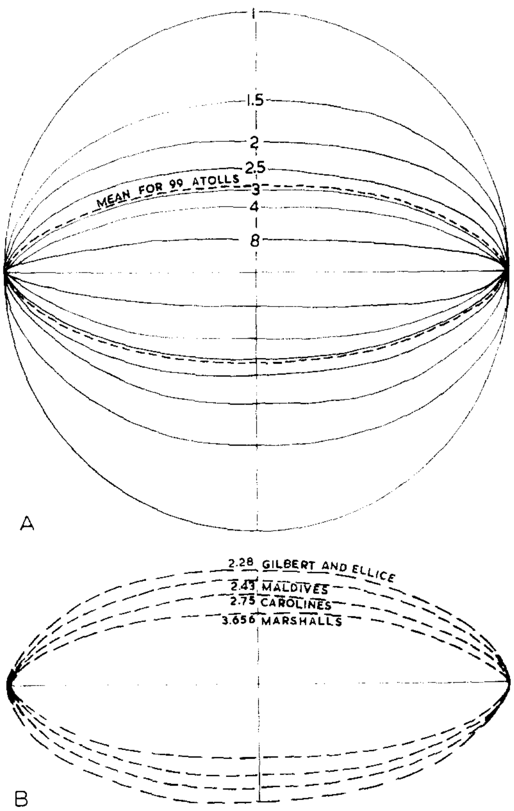

Fig.10. A. Families of ellipses showing values of I_e from 1–8 when $2a$ is constant and b is variable. The mean I_e value for the sample atolls is shown: the modal class of I_e values is 1.5–2.0. B. Ellipses drawn for the mean I_e values for four main atoll groups: Marshall, Caroline, Maldive, and Gilbert and Ellice groups.

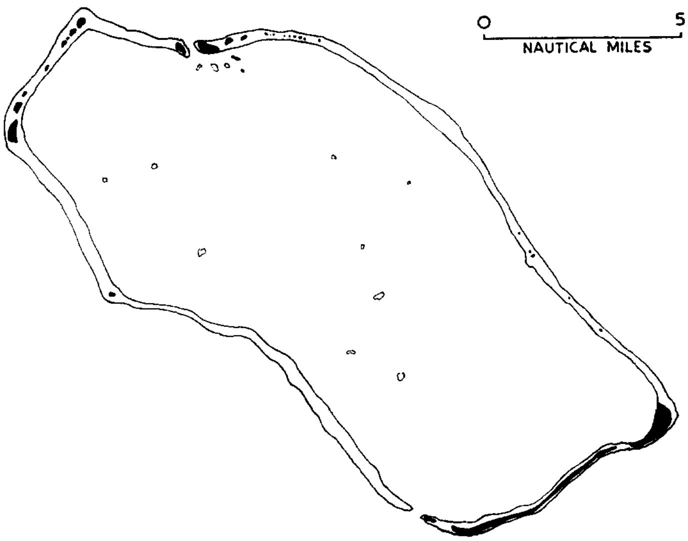

Fig.11. Satawan Atoll, a suggested "typical" atoll on the basis of shape measurements. Satawan is placed among the median nine atolls by more methods than any other atoll. Reproduced from the Admiralty Chart No.909 with the sanction of the Controller of H. M. Stationery Office and the Hydrographer of the Navy.
$F = 0.334$; $R_c = 0.741$; $R_e = 0.651$; I_e 2.352; $I_r = 28.33$; $S_1 = 14.77$; $S_2 = 18.33$; $S_3 = 9.86$; $S_1^2 = 42.37$; $S_2^2 = 25.55$; $S_3^2 = 44.55$.

polygon method is cumbersome, slow to calculate, and, most disadvantageous, results in a set of six indices (for an octogon), on which it is difficult to perform further operations. For a relatively homogeneous set of shapes, such as atolls, it is insufficiently discriminative to be valuable: this could be improved by using a greater number of vertices, with consequently a better fit, but this would increase the final number of indices and make the method even more unwieldy. The radial line index (I_r) provides a single index which is readily calculated, but it does not appear to be sufficiently discriminatory: Boyce and Clark's values for highly diverse geometric figures lie within the range of variation for fairly simple atoll shapes. It seems probable that I_r values do not have unique significance, and that different shapes may have the same I_r values. The ellipticity index I_e appears most satisfactory: it provides a single index, is readily calculated, and all the nine median atolls selected by it are selected by one or more of the other methods. Even more important, indices may be re-interpreted in shape terms, which is almost impossible with, for example, the fitted polygon method.

COMMENT ON INTERPRETATION

An impression of the range of atoll shapes may be gained from Fig.10, which gives a family of ellipses drawn for a fixed value of a and varying values of b: a circle has a value of 1.0, and the mean value for the sampled atolls was 2.867. Because of the skewed distribution the modal class of 1.5–2.0 is probably a better indication of central tendency of atoll shapes. The actual atoll shapes used were also ranked in terms of the shape measures used, and in each case the pattern of ranking, in spite of individual variation, was similar. Satawan Atoll (Fig.11) is the only atoll to appear in the median nine atolls as ranked by F, I_e and I_r numbers: Satawan is therefore suggested as a "typical" atoll shape.

The results were also broken down by island group, and mean values derived for F, R_c, R_e, I_e and I_r values for atolls in the Caroline, Marshall, Maldive, and Gilbert and Ellice groups. Results of this analysis are given in Table III, and mean I_e values are drawn in Fig.10. From this it is apparent that the most elongate atolls are those in the Marshall Islands, and the most rounded those in the Gilbert and Ellice Islands. In general, atolls are more elongate than would be subjectively apparent: the round atolls, such as Ebon and Pratas, are certainly atypical, as are the more elongate atolls such as Lighthouse and Raroia.

TABLE III

SUMMARY OF ATOLL-SHAPE DATA BY ISLAND GROUPS

Atoll group	*Number in sample*	F *(mean)*	R_c *(mean)*	R_e *(mean)*	I_e *(mean)*	I_r *(mean)*
Caroline	27	0.348	0.554	0.616	2.750	30.38
Marshall	16	0.395	0.524	0.593	3.656	33.56
Maldive	17	0.375	0.644	0.677	2.429	22.13
Gilbert and Ellice	9	0.324	0.478	0.641	2.284	30.34
Total sample						
Means	99	0.349	0.569	0.638	2.867	29.78
Standard deviation		0.133	0.186	0.142	—	14.73

CONCLUSIONS

This study has, therefore, demonstrated the fundamental homogeneity of atoll shapes, which is not affected by the existence of a few atolls with the unusual shapes noted by Wiens. This homogeneity of shape may be used as a starting point for the derivation of a generalised atoll form in any attempt to construct a model of atoll ecology and dynamics. Shape studies also suggest that atolls may vary significantly between island groups, and this should be taken into account in any theoretical constructions on atoll morphology. The use of the shape measures derived here can provide a starting point for the investigation and generalisation of atoll data, for while atolls have so far been generally studied individually, sufficient data have accumulated for generalisation to begin.

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